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SEARCH FOR NUCLEARITES WITH THE SLIM DETECTOR

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Abstract We discuss the properties of cosmic ray nuclearites, from the point of view of their search with large nuclear track detector arrays exposed at different altitudes, in particular with the SLIM experiment at the Chacaltaya high altitude lab (5290 m a.s.l.). We present calculations concerning their propagation in the Earth atmosphere and discuss their possible detection with CR39 and Makrofol nuclear track detectors.

1 Introduction

Strange Quark Matter (SQM) could be the ground state of quantum chromodinamics [1]. The initial hypothesis assumed that SQM is made of u, d and s quarks in nearly equal proportions (with some electron component in weak equilibrium). Recently it was shown that the so called "color-flavor locked" (CFL) SQM, characterized by a Cooper-like pairing between different quarks, could be even more stable [2].

SQM is expected to have a density slightly larger than ordinary nuclear matter [1, 2]; the relation between the mass M of SQM lumps and their baryonic number A ($\simeq$ one third of the number of constituent quarks) would be

$$M(\text{GeV}) \lesssim 0.93A. \tag{1}$$

It was hypothesized that "nuggets" of SQM, with masses from those of heavy nuclei to macroscopic values, produced in the Early Universe or in violent astrophysical processes, could be present in the cosmic radiation (the so-called

nuclearites) [3] [1]. SQM should have a relatively small positive electric charge, eventually neutralized by an electron cloud. If the size of the SQM is large (corresponding to masses $M \gtrsim 10^7$ GeV), some of the electrons could be in chemical equilibrium inside the quark core [4]. Nuclearites larger than 1 Å, ($M \geq 8.4 \times 10^{14}$GeV) would contain all electrons inside the quark core and thus would be completely neutral [3]. A qualitative picture of nuclearites may be found in [5].

An upper limit for the flux of nuclearites may be obtained assuming that they represent the main contribution to the local Dark Matter (DM) density, $\rho_{DM} \simeq 10^{-24}$ g cm^{-3} [3],

$$\Phi_{max} = \frac{\rho_{DM} v}{2\pi M}, \tag{2}$$

where v and M are the nuclearite average velocity and mass, respectively.

The aim of this note is to discuss the possibility to detect nuclearites using large area Nuclear Track Detectors (NTDs) at mountain altitude (in particular with the SLIM experiment [6, 7, 8]). We classify nuclearites in three different mass ranges (and sizes).

- **Low mass nuclearites (LMNs), or *strangelets***, with masses between those of ordinary nuclei ($A \lesssim 300$) and a multi-TeV mass. The upper bound is an ad-hoc one; an indirect definition of this category could be that many of the properties of LMNs would contradict the assumptions made in [3] summarized in Section 3. We shall discuss the case of LMNs in Section 2.

- **Intermediate mass nuclearites (IMNs) or, simply *nuclearites***, with masses large enough to be well described by the hypothesis made in [3], but smaller than about 10^{22} GeV (for $M > 10^{22}$ GeV nuclearites would traverse the entire Earth). The mass lower limit of IMNs may be about 10^8 GeV, above which nuclearites could be detected by experiments performed in the upper atmosphere (see also Fig. 6). Assuming that they would travel in space with typical galactic velocities ($\beta = v/c \simeq 10^{-3}$), they would be stopped by the Earth, so they would reach detectors only from above. The main properties of IMNs are summarized in Section 3.

- **"Macroscopic" nuclearites**, with masses $M > 10^{22}$ GeV; assuming galactic velocities, such nuclearites would traverse the Earth. They differ from IMN's only by size. We shall not discuss this case, since the expected sensitivity of SLIM (and of similar experiments) will not compete with the limit obtained by MACRO in this mass range [9, 10, 11].

[1] The attention of the authors was mostly focused on relatively large mass nuggets of SQM, so that the microscopic properties of the nuclearites would not be relevant. This is suggested also by the name they proposed for the newly postulated objects, "nuclearites": a combination between "nuclei" and "meteorites". Note that a nuclearite is an electrically neutral state composed of a SQM "nucleus" and electrons.

Much heavier nuclearites ($M \gtrsim 10^{28}$ GeV) could be observed as abnormal sismic events [13, 14] [2].

Calculations describing the production (through binary strange stars tidal disruption) and the galactic propagation of cosmic ray nuclearites were recently published [17]. The results could be valid as orders of magnitude for the entire mass range of interest; we shall use the predicted fluxes (at the Earth level) as reference values.

Searches for nuclearites (mostly IMNs) were performed by different experiments [15, 16]. The best flux upper limit was set by the MACRO experiment: for nuclearites with $\beta \simeq 10^{-3}$, the 90% C.L. upper limit is at the level of 2×10^{-16} $\mathrm{cm^{-2}sr^{-1}s^{-1}}$ in the mass range 10^{14} GeV $< M < 10^{22}$ GeV [9, 10, 11][3].

SLIM is a large area experiment (440 $\mathrm{m^2}$) installed at the Chacaltaya high altitude laboratory since 2001; an additional 100 $\mathrm{m^2}$ were installed at Koksil, Pakistan, since 2003 [4]. With an average exposure time of about 4 years, SLIM would be sensitive to a flux of downgoing exotic particles (magnetic monopoles, nuclearites and Q-balls) at a level of 10^{-15} $\mathrm{cm^{-2}sr^{-1}s^{-1}}$.

2 Low mass nuclearites (LMNs)

SQM should be stable for all masses larger than about 300 GeV [3]. Nuclearites with masses up to the TeV region could be ionized and could be accelerated to relativistic velocities by the same astrophysical mechanisms of normal nuclei of the primary cosmic radiation (CR).

LMNs would interact with detectors (in particular NTDs) in ways similar to heavy ions, but with different Z/A. There are different calculations in relative agreement with a possible candidate with $M \simeq 370$ GeV and a charge $Z \simeq 14$ [18].

In ref. [4] SQM is described in analogy with the liquid-drop model of normal nuclei; the obtained charge versus mass relation is shown in Fig. 1 by the solid line, labeled "(1)". Other authors found different relations: $Z \simeq 0.1A$ for $A \lesssim 700$ and $Z \simeq 8A^{1/3}$ for larger masses [19]: this charge to mass relation is shown in Fig. 1 as the dashed line, labeled "(2)". In [2] it was assumed that quarks with different color and flavor quantum numbers form Cooper pairs inside the SQM (the so-called color-flavor locked phase), increasing the stability of the strangelets. In this case, the charge relation would be $Z \simeq 0.3A^{2/3}$, shown as the dash-dotted line in Fig. 1 labeled "(3)".

Several CR experiments reported candidate events that would suggest anomalously low charge to mass (Z/A) ratios, which could correspond to those expected for SQM [4]. Such candidates are reviewed in [20, 21]. As strangelets with masses not much higher than those of ordinary nuclei could have the same

[2] In ref. [13] there was a claim of observing a candidate, but it was discarded in [14] because of timing uncertainities.

[3] This is twice the flux limit obtained for relativistic GUT magnetic monopoles [12], as it refers only to down-going nuclearites.

[4] The calculations presented in this report refer to the Chacaltaya location only.

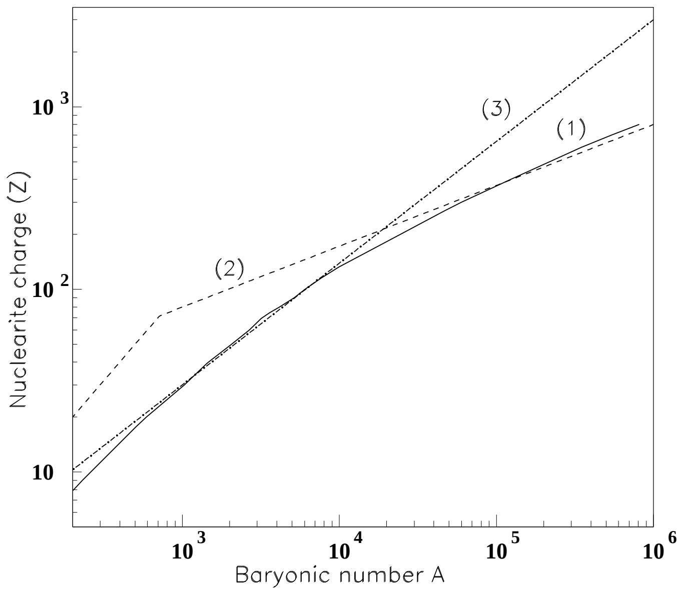

Figure 1: Low mass nuclearites (LMN) charge versus mass for different hypotheses discussed in refs. [4, 19, 2]. See text for details.

origin as CR heavy nuclei, their abundances in the cosmic radiation could follow the same mass dependence, $\Phi \propto M^{-7.5}$, [20]. The existing candidates do not contradict such an hypothesis. The solid line in Fig. 2 is the expected flux versus nuclearite mass, assuming that the above assumptions are correct. Obviously, as the mass becomes larger, the production mechanisms for normal cosmic rays cannot anymore apply to nuclearites.

Different nuclearite flux estimates were recently published [17]. They are based on the hypothesis that large nuclearites (with masses $10^{-5} - 10^{-2}$ solar masses) are produced in binary strange stars systems, before their gravitational collapse. The propagation inside the galaxy considers also the escape, spallation (through which smaller nuclearites are produced) and re-acceleration mechanisms. Nuclearite decays are not considered, as SQM is supposed to be absolutely stable. The predicted strangelet fluxes around the Earth are presented in Fig. 2 for"normal" and CFL strangelets as the dashed and the dot-dashed lines, respectively. The small differences (that vanish for larger masses, when nuclearites become completely neutral) originate in the slightly different charge-to-mass ratios (see Fig. 1).

LMNs would be similar to normal nuclei, except their low Z/A values and, most likely, different abundances. If they interact with the Earth's atmosphere in the same way as CR nuclei, they would not reach experiments at mountain altitude.

Two different (and opposite) theoretical scenarios, both consequences of the hypothesis that SQM is more stable than ordinary nuclear matter, were intro-

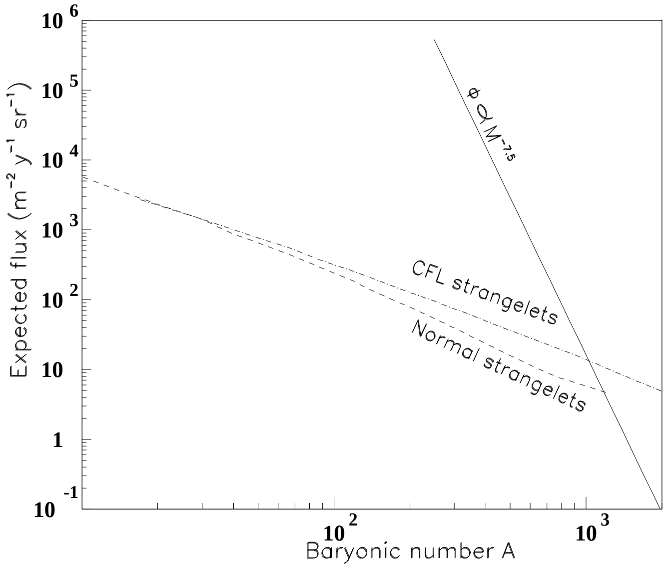

Figure 2: Expected fluxes for LM strangelets in the CR near the Earth. The solid line corresponds to the assumption that their abundances follow the same rule as heavy CR nuclei [20]. The dashed and dot-dashed lines are from Ref. [17], and refer to "normal" and CFL strangelets.

duced in order to allow deep penetration of small nuclearites in the atmosphere; none of those mechanisms would allow them anyway to reach sea level; such objects could be found only in high altitude experiments.

2.1 Mass and size decrease of nuclearites during propagation

In [20] it was assumed that small nuclearites could penetrate the atmosphere if their size and mass are reduced through successive interactions with the atomic air nuclei. The proposed scenario is based on the spectator-participant picture. Two interaction models are considered: quark-quark (called "standard"), and collective (called "tube-like"). At each interaction the nuclearite mass is reduced by about the mass of a Nitrogen nucleus (in the "standard" model), or by more (in the "tube-like model"), while the spectator quarks form a lighter nuclearite that continues its flight with essentially the same velocity as the initial one. Once a critical mass is reached ($A \simeq 300$ - 400) neutrons would start to evaporate from strangelets; for $A < 230$ the SQM would become unstable and decay into normal matter. In ref. [22] an estimate was made of the sensitivity of the SLIM experiment [6]: the mass number of a nuclearite penetrating the atmosphere down to the Chacaltaya lab would be one seventh of that it had at the top of the atmosphere.

The CR39 used in SLIM is sensitive to particles with a Restricted Energy Loss (REL) larger than 200 MeV g^{-1} cm^{2} [5]. Table 1 presents the minimum

[5] The threshold of a NTD depends on the etching conditions. A relatively high threshold for

detectable mass for strangelets reaching SLIM.

A/Z hypothesis	A (at SLIM)	A_0 (top of the atmosphere)	Φ $\mathrm{cm^{-2}s^{-1}sr^{-1}}$ (Ref. [17])	Φ $\mathrm{cm^{-2}s^{-1}sr^{-1}}$ (heavy nuclei)
Liquid-drop or CFL Refs. [4, 2]	$\simeq 587$	$\simeq 4109$	$6 \times 10^{-12} (CFL)$ 3×10^{-12} (normal)	2.4×10^{-15}
"Normal" nuclearites Refs. [19, 2]	$\simeq 210$	$\simeq 1470$	9.5×10^{-12}	2.8×10^{-12}

Table 1: The minimum strangelet masses detectable in SLIM assuming different A/Z relations. The masses at the top of the atmosphere are estimated as in Ref. [20], and the expected fluxes are computed as in Ref. [17], and assuming the same mass abundances of ordinary cosmic ray nuclei.

2.2 Accretion of neutrons and protons during propagation

A completely different propagation scenario was proposed in [21]. The authors assume that small mass nuclearites would pick-up nuclear matter during interactions with air nuclei, rather than loosing mass. After each interaction, the nuclearite mass would increase by about the atomic mass of Nitrogen, with a corresponding slight reduction of velocity. As the mass grows larger, the loss in velocity becomes smaller. They estimate that a strangelet of an initial $A \simeq 64$ and an electric charge of about +2 could arrive at about 3600 m a.s.l. with $A \simeq 340$ (3600 m is the altitude of a proposed NTD experiment in Sandakphu, India [21]). This mechanism would also imply an increase of the electric charge of the strangelet, thus an increase of the Coulomb barrier; this may be the main difficulty of this scenario. The flux according to [17] would be of the order of 10^{-9} $\mathrm{cm^{-2}s^{-1}sr^{-1}}$, and higher.

About 171 $\mathrm{m^2}$ of the SLIM modules exposed for an average time of 3.5 years were removed, processed and analized. No cadidate survived. The 90% C.L. flux upper limit for downgoing nuclearites (LMNs and IMNs) is at the level of 4×10^{-15} $\mathrm{cm^{-2}sr^{-1}s^{-1}}$. This would disfavor the "accretion scenario", and most of the hypotheses quoted in Table 1.

3 Intermediate mass nuclearites (IMNs)

In [3] was postulated that elastic collisions with the atoms and molecules of the traversed medium are the only relevant energy loss mechanism of non-relativistic nuclearites with large masses,

$$\frac{dE}{dx} = -\sigma \rho v^2, \tag{3}$$

CR39 was chosen in order to reduce the background due to recoil tracks, neutron interactions and the ambient radon radioactivity.

where ρ is the density of the traversed medium, v is the nuclearite velocity and σ is its cross section:

$$\sigma = \left\{ \begin{array}{ll} \pi(3M/4\pi\rho_N)^{2/3} & \text{for } M \geq 8.4 \times 10^{14} \text{ GeV (corresponding to } R_N \simeq 1 \text{ Å)} \\ \pi \times 10^{-16}\text{cm}^2 & \text{for lower mass nuclearites} \end{array} \right. , \tag{4}$$

with $\rho_N = 3.6 \times 10^{16}$ g cm^{-3}. As the chemical potential of the s quarks in SQM is slightly larger than for u and d quarks, SQM is always positively charged [3], thus the cross section for nuclearites with $M < 8.4 \times 10^{14}$ GeV is determined by their electronic cloud.

The following calculations apply to nuclearites of mass M much larger than typical nuclear masses and $\beta \simeq 10^{-3}$; effects due to possible ionization or mass variations during their flight in the atmosphere are negligible. We also neglect the gravitational acceleration of nuclearites by the Earth.[6]

A nuclearite of mass M entering the atmosphere with an initial velocity $v_0 << c$, after crossing a depth L will be slowed down to

$$v(L) = v_0 e^{-\frac{\sigma}{M}\int_0^L \rho dx} \tag{5}$$

where ρ is the air density at different depths, and σ is the interaction cross section of Eq. 4.

We consider the parametrization of the standard atmosphere from [23]:

$$\rho(h) = ae^{-\frac{h}{b}} = ae^{-\frac{H-L}{b}}, \tag{6}$$

where the constants are $a = 1.2 \times 10^{-3}$g cm^{-3} and $b \simeq 8.57 \times 10^5$ cm; H is the total height of the atmosphere ($\simeq 50$ km). The integral in Eq. 3 may be solved analytically:

$$\int_0^L \rho dx = abe^{-\frac{H}{b}} \left(e^{\frac{H-h}{b}} - 1 \right). \tag{7}$$

Fig. 3 shows the velocity with which nuclearites of different masses reach heights corresponding to typical balloon experiments (for instance CAKE, 40 km [24]), possible experiments using civilian airplanes (11 km), the Chacaltaya lab (SLIM, 5.29 km [6]) and at sea level. A computation valid for MACRO [10] (at a depth of 3400 mwe) is also included. The velocity thresholds for detection in CR39 (corresponding to REL = 200 MeV g^{-1} cm^2)[7] and in Makrofol (REL = 2500 MeV g^{-1} cm^2) are shown as the dashed curves.

The decrease of the velocity thresholds for nuclearite masses larger than 8.4×10^{14} GeV is due to the change in the nuclearite cross section, according Eq. 4.

An experiment at the Chacaltaya altitude lowers the minimum detectable nuclearite mass by a factor of about 2 with respect to an experiment performed at sea level. If the mass abundance of nuclearites decreases strongly with increasing mass this could yield an important increase in sensitivity.

[6] Assuming a nuclearite mass of 1 ng (about 5.6×10^{14} GeV) arriving at an altitude of 5000 m with $\beta = 10^{-3}$, the gravitational energy gain would represent less than about 1.5×10^{-3} of the energy loss in the atmosphere; for $\beta = 10^{-4}$ (near the Makrofol threshold) this ratio is about 0.15.

[7] We recall that in the low background conditions of the Gran Sasso Lab, in the case of the MACRO experiment the CR39 detection threshold was set to 50 MeV g^{-1} cm^2

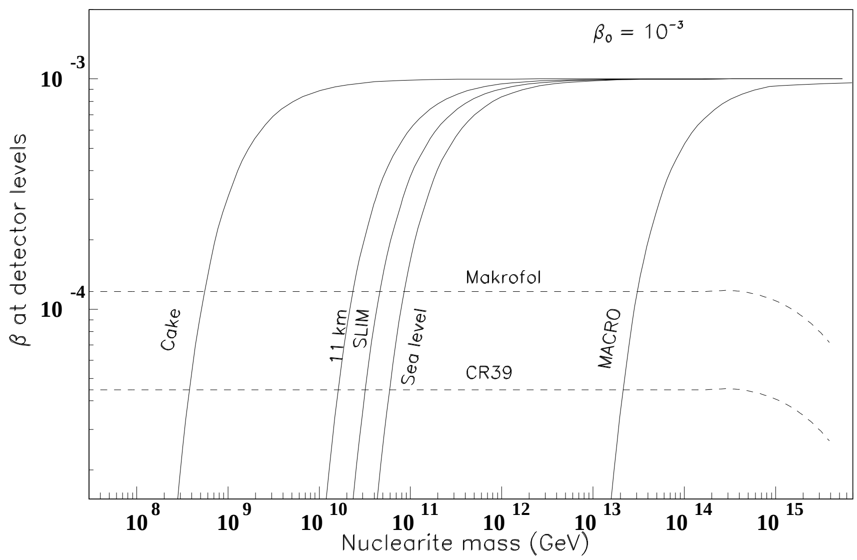

Figure 3: Solid lines: arrival velocities of IMNs at different depths versus nuclearite mass, assuming an initial velocity outside the atmosphere of $\beta = 10^{-3}$. The nuclearites are supposed to come from above, close to the vertical direction. The dashed lines show the detection thresholds in CR39 (in the SLIM etching conditions) and Makrofol.

The nuclearite detection conditions in CR39 (expressed as the minimum entry velocity at the top of the atmosphere versus the nuclearite mass) for different experimental locations is shown in Fig. 4. In this case, the constraint is that nuclearites have the minimum velocity at the detector level in order to produce a track; we remind that for all experiments the REL threshold for detection in CR39 is set to 200 MeV g^{-1} cm^2 (it was 50 MeV g^{-1} cm^2 in the case of MACRO).

Fig. 5 shows the same for the Makrofol track etch detector. The detection condition corresponding to CR39 at balloon altitude (CAKE) is also shown.

4 Conclusions

SLIM is a large area NTD experiment, taking data at the Chacaltaya Cosmic Ray Laboratory. In this note we investigated the possibility to search for nuclearites with SLIM, assuming two nuclearite mass regions.

Low mass nuclearites could reach mountain altitudes assuming some peculiar interaction mechanisms in the atmosphere. They would produce in NTDs tracks sim-

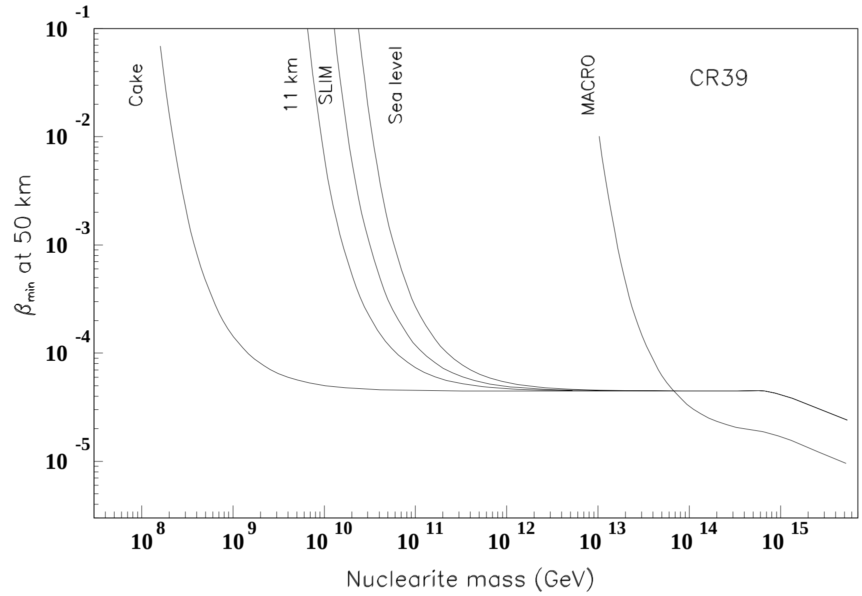

Figure 4: Nuclearite detection conditions in CR39, for experiments located at different altitudes.

ilar to those expected from fast monopoles or relativistic heavy nuclei[8] [6]. SLIM will reach a sensitivity at the level of about 10^{-15} cm^{-2}s^{-1}sr^{-1} for a flux of nuclearites coming from above. In the absence of a LMN candidate, SLIM would rule out the propagation mechanisms hypothesized. SLIM will be also sensitive to different strangelet structure hypotheses ("normal" or CFL, different Z/A predictions), and could validate or not the production and propagation model proposed in [17].

Intermediate mass nuclearites, entering the Earth atmosphere with typical galactic velocities might be detected by large area NTDs as SLIM. The minimum detectable nuclearite mass is very sensitive to the experiment location: an underground experiment like MACRO could search for nuclearites with $M \geq 10^{14}$ GeV, the minimum mass accessible to ANTARES [25] is of few 10^{13} GeV. Detectors at ground level, or better at mountain altitudes like SLIM, would decrease the mass threshold to few 10^{10} GeV; balloon experiments are needed to reach few 10^{8} GeV, while lower mass searches have to be done outside the Earth atmosphere.

SLIM is sensitive to non relativistic ($\beta \lesssim 10^{-3}$) IMNs with masses larger than 3×10^{10} GeV; the large REL of IMNs in NTDs and their property to produce identical tracks in all the detector sheets in a stack could yield experimental signatures with low background.

Nuclearites with masses between few TeV and about 10^{8} GeV are not considered

[8]Note that relativistic nuclei present in the CR cannot penetrate the Earth's atmosfere till the Chacaltaya level.

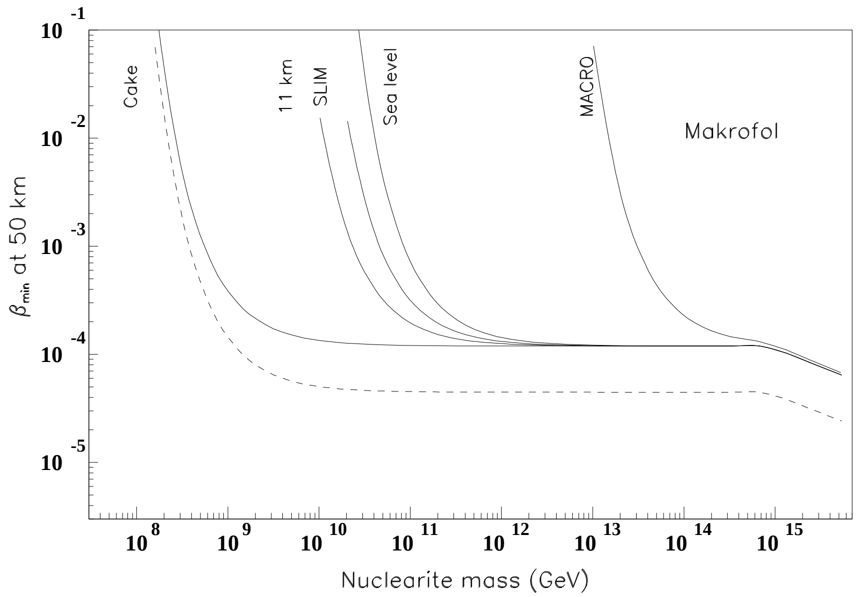

Figure 5: Nuclearite detection conditions in Makrofol, for experiments located at different altitudes. The dashed curve (shown for comparison) corresponds to CR39 in CAKE.

at this time. In the low part of this mass range, they could still be accelerated to relativistic velocities by cosmic fields, and could be detected as LMNs in high altitude experiments. For larger nuclearite masses, one would expect the velocity to get close to the galactic one, and thus such nuclearites would not be able to reach the detector. A search for nuclearites in this mass range could, in principle, be done in space experiments, such as the AMS detector on board of the International Space Station [26].

Fig. 6 summarizes the conclusion, showing the accessible nuclearite mass regions for different experiments.

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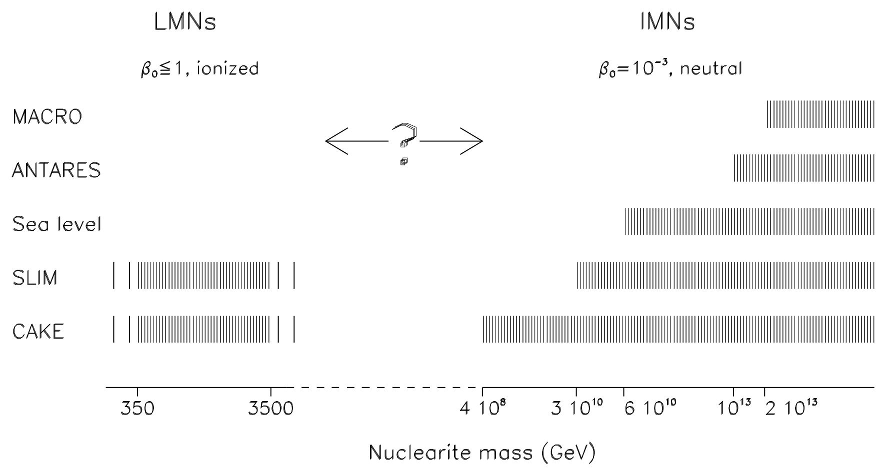

Figure 6: Approximate nuclearite mass regions, accessible to different experiments, (The drawing is not to scale).

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